

On-road Ring-of-Fire measurements of following SUVs at moderate distances

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ABSTRACT

In this study, a proof-of-concept application of Shake-the Box measurements employing the 'Ring-of-Fire' technique was performed to capture the full wake of a sport utility vehicle (SUV) in a single driving and a following configuration, travelling at a speed of 13.89 m/s (50 km/h). The study also introduces novel processing techniques of such measurements, including the lateral alignment of the multiple measurement runs directly within the 3D Calibration. A hybrid hardware approach was utilized, combining low-speed PIV cameras with a high-speed illumination system, with the aim of improving the practicability and ease of use of such a system, while ensuring sufficient spatial resolution along the out of plane axis. Eight 25-megapixel (5328 x 4608) cameras were used, operated at a reduced resolution of 2112x 1024 pixels and an acquisition frequency of 150 Hz, covering a cross-sectional field of view of 3.7 m x 1.6 m. Two configurations were compared, where on one, a Subaru Solterra was tested standalone at 13.89 m/s. The second configuration also captured the wake of the Subaru Solterra, but in a configuration where the Solterra was following a Mazda CX-5 with a distance of 20 m at again 13.89 m/s.

1. Introduction

Platooning car aerodynamics has gained recent attention due to its relevance to energy efficiency, particularly in the context of electromobility. The aerodynamic effects experienced when driving in the wake of another vehicle constitute a topic of considerable research interest. Multiple studies have been performed to investigate the aerodynamic effects of driving behind passenger and commercial vehicles (Bounds et al., 2021; Davila et al., 2013; Ebrahim et al., 2020)

On-road measurements for road vehicles have been shown to yield valuable information on road vehicle aerodynamics. Multiple studies have demonstrated the viability and capabilities of Ring-of-Fire Particle Image Velocimetry (PIV) and Lagrangian Particle Tracking (LPT) measurements for on-road aerodynamic testing (Sciacchitano et al. 2015; Hüttig et al., 2023, 2025; Butcher et al., 2025;

Erdogdu et al., 2025). Most commercial automotive wind tunnels are designed for single-vehicle testing (Wiedemann & Potthoff, 2003; Nagaoka et al., 2024), and the inherently variable nature of on road conditions introduces challenges in achieving reproducibility, resulting in a scarcity of experimental investigations on platooning vehicle aerodynamics. Performing such experiments on platooning vehicles creates an even greater challenge for on-road measurements.

The experimental work presented here aims to investigate the capabilities of performing on-road Ring-of-Fire measurements on following vehicles over a moderate following distance. The study was carried out in form of a large-scale Shake-the-Box (STB) (Novara et al., 2023; Schanz et al., 2016) measurement within the Catesby tunnel (Shimoyama, 2026) in the UK. The Catesby tunnel, measuring 2.7 km in length, is a specialized test facility, which was repurposed from a former railway tunnel. The tunnel provides an optimal test section for reproducible on road aerodynamic investigations. Experiments were performed with a Mazda CX-5 as the leading, and the Subaru Solterra as the following vehicle. An 8-camera STB system was utilized for the experiments.

2. Experimental Setup

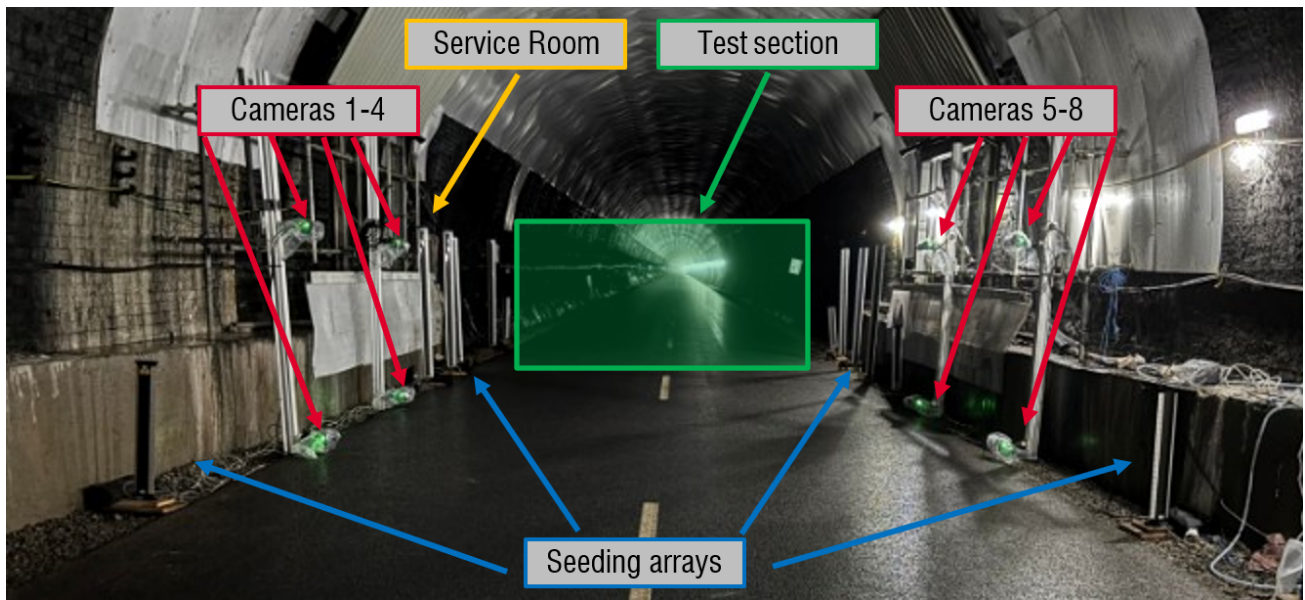


Figure. 1 Experimental set-up within the Catesby tunnel.

The experimental set-up was installed within the tunnel at a distance of 800 m from the tunnel entrance, as shown in Figure 1. Eight acquisition cameras (Imager CX3p-25) were positioned in the tunnel, with four cameras mounted on each side. The cameras have a native resolution of 5328 x 4608 pixels and were operated with 2x2 hardware binning. Furthermore, the region of interest was reduced to 2112 x 1024 pixels to maximize the acquisition frequency. The cameras were capturing in double-frame mode with an acquisition frequency of 150 Hz. The time separation (Δt) between two pulses was set to 500 μ s.

The measurement area was seeded with helium-filled soap bubbles (HFSB) (Bosbach et al., 2008) generated by a total number of 240 nozzles distributed over 12 linear nozzle arrays (LNA). Six of those LNAs were placed on each side of the tunnel. Ten of these LNAs (five on each side) were distributed over a 5 m longitudinal span of the tunnel, providing a seeded region of approximately 5 m adjacent to the test section. The remaining two LNAs were placed further upstream to ensure adequate seeding entering the vehicle wake. The seeding arrays were connected with flexible piping, allowing flexible placement and repositioning of single units as required. Each side of the tunnel was supplied by a dedicated HFSB controller unit (Fluid Supply Unit — FSU). For illumination of the bubbles, a high speed dual cavity Photonics Industries DM30 laser was employed. A complete list of experimental apparatus is provided in Table 1. The acquisition PC, the high-speed laser, a dehumidifier, and air compressors were placed within a climate-controlled service room on the side of the tunnel. The laser light sheet was propagated from a small cutout on the service room door and had an average thickness of 35 mm. A light barrier was mounted approximately 20 m upstream from the test section to trigger the measurement system.

Table 1 Overview of the components of the employed measurement system.

Component	Amount	Company	Type
<i>Camera</i>	8x	LaVision	CX3p-25 MP
<i>Lens</i>	8x	Samyang	4x 24 mm + 4x 35 mm
<i>Timing Unit</i>	1x	LaVision	Programmable Timing Unit (PTU) 11
<i>Laser</i>	1x	Photonics Industries	DM30 - 30 mJ/Pulse
<i>Seeding Device</i>	2x	LaVision	HFSB Controller - Fluid Supply Unit
<i>Seeding Arrays</i>	12x	LaVision	7x 2m + 5x 1m Linear Nozzle Arrays
<i>Light Barrier</i>	1x	LaVision	-
<i>Calibration Plate</i>	1x	LaVision	2D -1188 x 765 mm
<i>Software</i>	-	LaVision	DaVis 11

3. Data Acquisition and Processing

Two configurations were captured during the experiments. In one case, a single vehicle drove through the test section with a cruising speed of 13.89 m/s (50 km/h). The interplane distance between two subsequent double frame images corresponds to a spacing of approximately 93 mm at an acquisition frequency of 150 Hz. In the other case, two vehicles travelled in convoy at the same speed with an approximate inter-vehicle separation of 20 m. The acquisition cameras at the specified operating resolution are capable of capturing double-frame images at up to 296 Hz,

which would enable measurements at the same plane spacing at a vehicle velocity of 27.778 m/s (100 km/h). However, for safety reasons and owing to the requirement for two drivers to operate simultaneously within the tunnel, the acquisition frequency was reduced to 150 Hz, corresponding to half the system's velocity capability. Five runs were captured for each configuration. Eight cameras were streaming to the Random Access Memory (RAM) of the acquisition pc in loop recording with external post trigger. A range of image index was captured once the vehicle passed through the light barrier, which sent a 5V TTL signal to the PTU. The allowed measurement duration was defined by RAM capacity of the Acquisition PC.

Ring-of-Fire measurements rely on repeating multiple runs to obtain sufficient statistical convergence through ensemble averaging multiple independent runs. The number of runs governs the convergence of the resulting volumetric average velocity vector fields. Experimentally, ensuring that the test vehicle moves on the exact same trajectory in between runs is nearly impossible with human drivers. Consequently, the vehicle position is slightly different on each run with respect to the PIV coordinate system. This creates a positional bias within the data, since the wake of the vehicle is in a slightly different position on each processed run. Therefore, the average vehicle wake cannot be captured accurately, if not corrected for. Furthermore, misalignments within the time domain also occur. This causes the vehicle to be in different positions within the same frame index of multiple runs (or in the same position on different frame indices). This issue is a result of either a slight velocity difference of the vehicle between the light barrier and the measurement plane, or a trigger jitter caused by the triggering system.

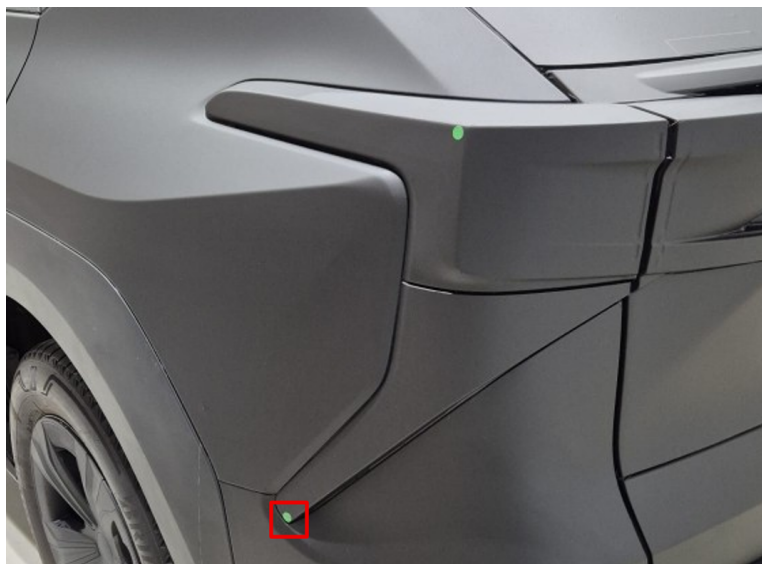


Figure 2. Reference marker positions on the Subaru Solterra. The marker used for the data alignment is highlighted by the red frame.

Green markers were placed as reference points on the vehicle during the measurements to perform the alignment work after acquisition. The markers used on the Subaru Solterra can be seen in Figure 2. These markers were placed to identify vehicle position on each run within the measurement coordinate system and were used as a reference for lateral vehicle alignment in between runs.

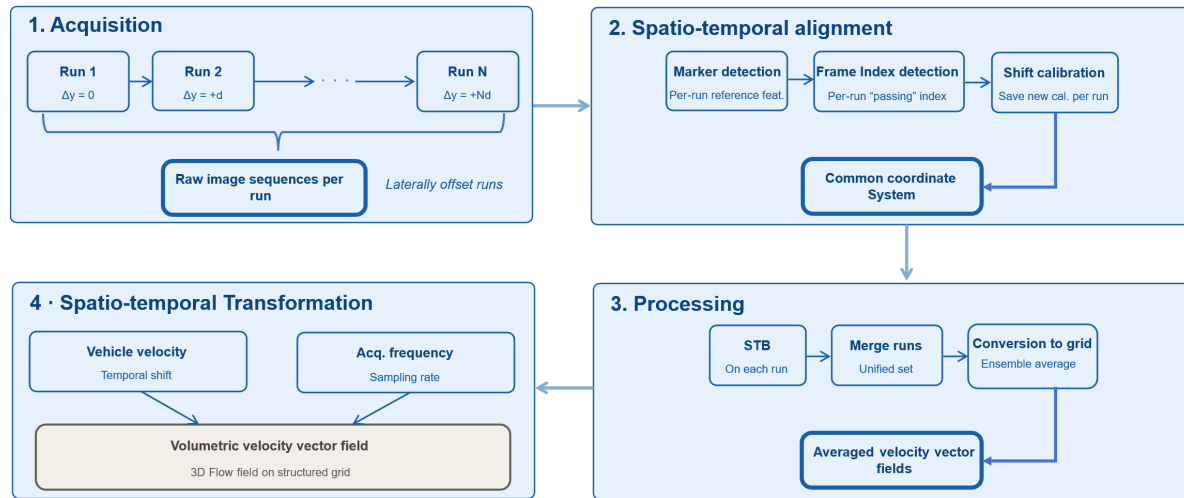


Figure 3 Processing workflow of Ring of Fire data

A novel method was developed to correct the lateral misalignments prior to data processing. This approach corrects lateral positional offsets directly at the calibration level, so that perspective corrected 2D images from individual runs are mapped onto a common coordinate system. In this procedure, the user identifies the position of a reference point on a minimum of two camera views per run. The active calibration is then used to triangulate the 3D coordinates of this feature. A new calibration is then created for each run, where the defined reference points of the test object overlap on a common coordinate system. The calibration ensures that the triangulated feature of the test object always aligns on the same coordinate, when perspective correction is performed on raw images. Additionally, a reference frame index is defined by the user, and a specified number of frames before and after this index are included. The runs are then processed individually via STB, resulting in the same number of datasets as the acquired amount of measurement runs. These datasets are then merged into a single STB track dataset, which contains all the processed runs as Lagrangian particle tracks. These tracks are then converted to a common grid using binning, during which the ensemble averaging is simultaneously performed. Finally, the binned data are interpolated onto a volumetric structured grid, incorporating the vehicle velocity and acquisition frequency to compute the vector field spacing and volume boundaries. The complete processing workflow is depicted in Figure 3.

For the current set of 5 runs of each measurement configuration, three cameras of all eight and the active calibration were used to triangulate the coordinates of the marker of each run. This alignment resulted in 5 new datasets, where each had a separate calibration, but were aligned both in time and space with respect to the reference point position on the vehicle. The Volume Self Calibration (VSC) was performed prior to the alignment operation, ensuring that the last modification on the calibration is the lateral correction.

Dual-pulse Shake-The-Box was performed on all the runs, and the data was merged within a single volume after processing. The ensemble LPT data was converted to a Cartesian grid using a binning approach with a final vector grid size of $64 \times 64 \times 1$ vectors. Hence, all particles from different z-positions were effectively averaged across the whole thickness of the light sheet. The in-plane vector spacing resulted to ~ 20 mm. Subsequently, an additional operation was used to perform a spatio-temporal coordinate transformation, resulting in a volumetric dataset of the vehicle wake. Additionally, Galilean transformation on the data was performed to transform the data from the tunnel reference frame to the vehicle reference frame.

4. Results

The processed dataset captures a total longitudinal wake extent of 23 m. For the present analysis, only the region within one vehicle length (4690 mm) downstream of the vehicle rear was considered. Within this region, the average number of Lagrangian particle tracks per time step was approximately 80,000 and 82,500 for the single-vehicle and following configurations, respectively. Within the wake core, where seeding density was lowest, the five processed and binned runs yielded approximately 150 tracks per bin for both configurations.

Figure 4 compares the air speed contours in the vehicle's longitudinal direction at the central cross-section ($Y = 0$) with and without a preceding vehicle. In real driving conditions, the wake entrains instationary air, resulting in negative values in the air speed contours within the loss region. Here, a Galilean transformation based on the vehicle speed is applied, and the results are represented as velocity contours, a form commonly used in wind tunnel tests and CFD analyses. Under the following condition, the velocity loss region is observed to expand downstream of the vehicle. In addition, the loss of velocity on the underfloor region is confirmed to be greater than that observed in single driving conditions. In particular, as the flow passes through the wake generated by the preceding vehicle, the underbody flow is significantly disturbed, resulting in a change in the energy balance relative to the upper-body flow. Consequently, the formation of a new vortex is observed in the lower downstream region beneath the strong vortex generated by the upper-body flow. It is suggested that, due to the reduced mean energy of the underbody flow,

a strong shear-induced upwash is not generated. However, the detailed mechanism remains a subject for future investigation.

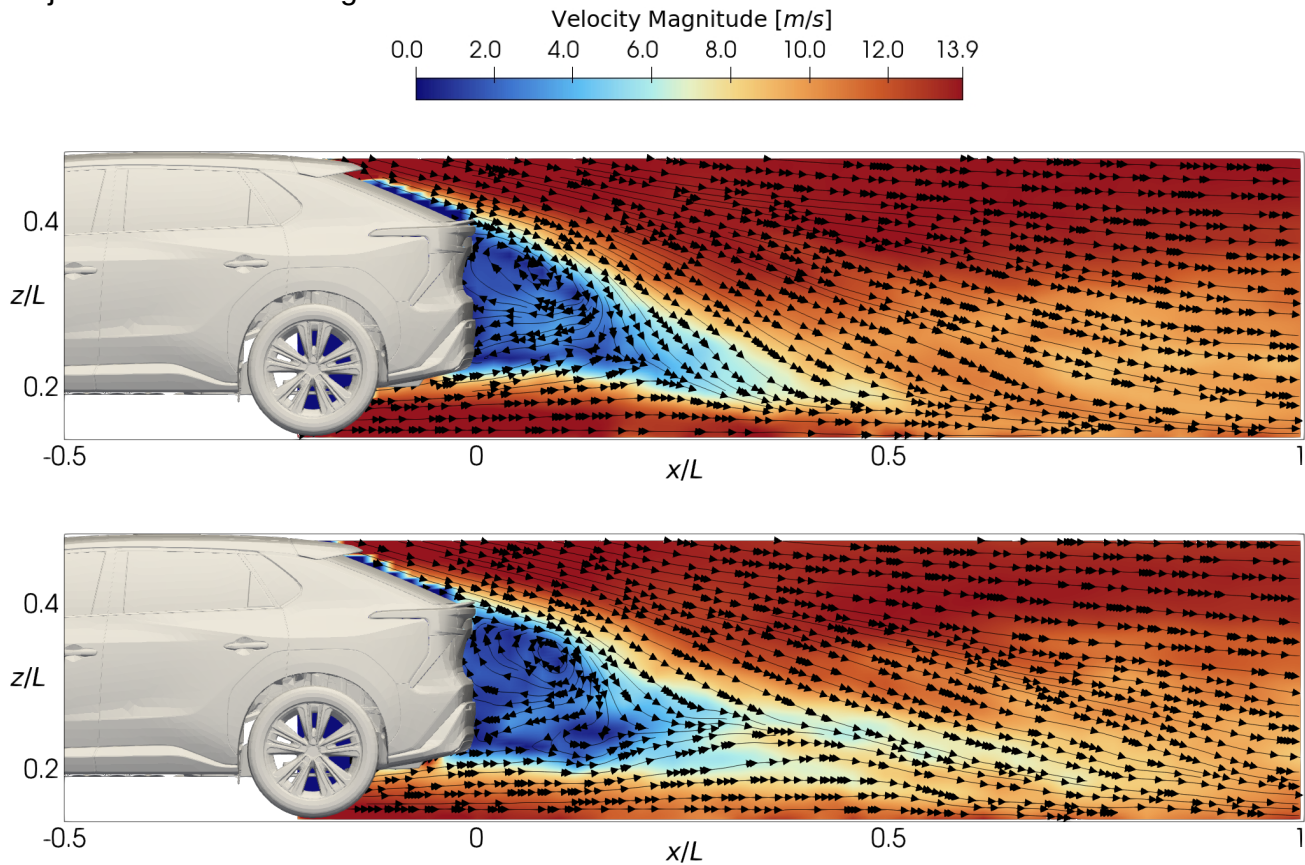


Figure 4 The near wake XZ Velocity Vector fields with streamlines at $Y=0$ (Symmetry axis), where the top corresponds to the single driving condition and bottom to the following configuration.

Figure 5 shows the air speed contours in the longitudinal direction at a downstream cross-section behind the vehicle, comparing with and without a preceding vehicle. A Galilean transformation is also applied. Under the following condition, the air speed of the free stream exhibits lower values, clearly indicating the influence of the wake generated by the preceding vehicle. As discussed earlier, this effect is particularly pronounced beneath the vehicle. Although the overall shape of the deceleration region does not change significantly, the extent of the deceleration region, including the area presumed to correspond to the tire wake, is observed to expand.

In the following condition, the upstream airflow is also considered to be entrained by the preceding vehicle rather than remaining stationary. Therefore, it cannot be conclusively determined whether this directly leads to an increase or decrease in aerodynamic drag, and further analysis is required. Nevertheless, the wake balance around the following vehicle is disturbed by the wake of the preceding vehicle, resulting in a deterioration compared to the wake structure under isolated driving conditions. In particular, the underbody flow, which has been meticulously optimized in

recent years to achieve low aerodynamic drag, is considered to be highly sensitive to such disturbances.

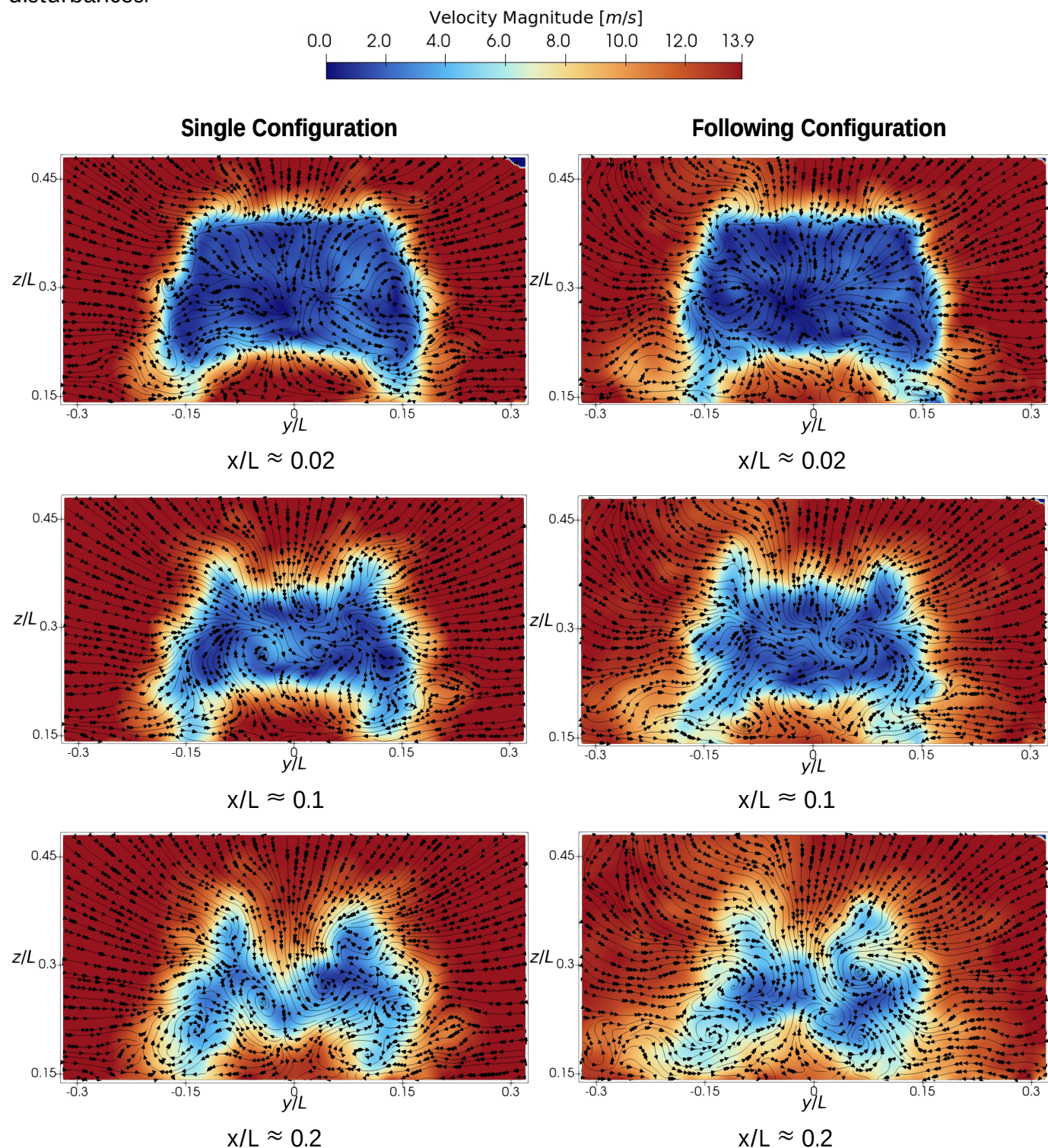


Figure 5 The YZ Velocity Vector fields of single driving and following configurations at $x/L \approx 0.02$, 0.1 and 0.2.

Finally, the iso-surface of velocity magnitude in the vehicle wake with and without a following condition is shown in Fig. 6. In order to identify flow structures associated with relatively strong

velocity losses, an iso-surface value of 5 m/s was selected, corresponding to approximately 36% of the freestream velocity. Under the following condition, the flow structures around the vehicle sides, the wheels, and the underbody become more complex, and the characteristic scales of the vortical structures are observed to become smaller.

The present measurement technique is therefore considered to have the potential to experimentally provide insight into changes in aerodynamic drag reduction and vehicle stability of the following vehicle from a flow-field perspective.

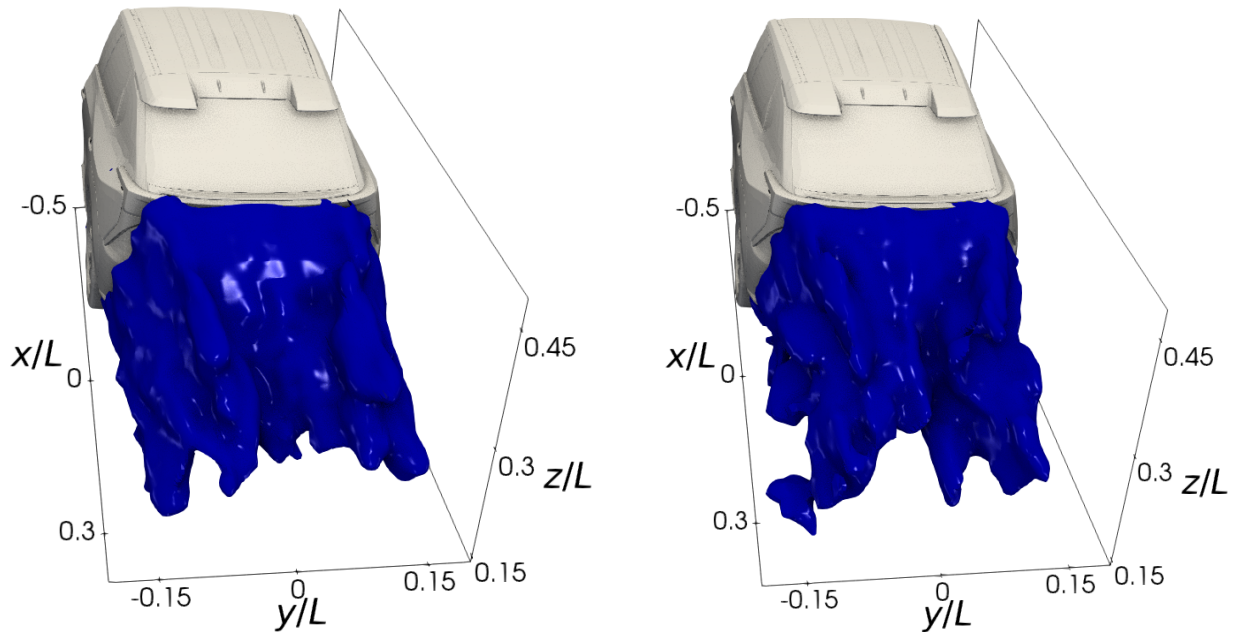


Figure 6 Velocity magnitude isosurfaces at $|V| = 5$ m/s of the single driving configuration (left) and the following configuration (right)

5. Conclusions

A proof-of-concept study was carried out to assess the feasibility of a Ring of Fire setup for on-road aerodynamic testing vehicles in a following configuration employing a Dual-pulse Shake-The-Box configuration. The feasibility of reducing the temporal resolution of cameras within Ring-of-Fire setups was also examined. The natural velocity decay in the vehicle wake requires the measurement system to have high temporal resolution only in the core of the near wake. Performing experiments at 50 km/h at 150 Hz resulting in a 93 mm plane spacing, has shown to be sufficient to capture the near wake. Moreover, the measurements in low velocity regime behind core wake region were sampled in a quasi-time resolved manner. Simplifying the temporal resolution requirements allows such complex setups to be much more feasible, in comparison to setups with large high-speed cameras with integrated memory. The measurement setup with dual pulse cameras show to provide a relatively simple setup process and ease of data handling while

providing acceptable temporal resolution. Additionally, the placement of four Cameras with proximity to the floor has shown to perform well in capturing data in the rear underbody region including the near wake of the tires. The flexible placement capabilities of the seeding system have also shown to be useful in optimizing the seeding array locations within the tunnel. The presented configuration resulted in no discarded runs due to insufficient or inhomogeneous seeding. The operational workflow and turnaround times of each run has shown that up to 80 measurement runs can be performed per test day.

A novel processing workflow has been developed that corrects lateral misalignments between measurement runs directly at the calibration level by modifying the calibration prior to any STB processing. This allows the alignment to be performed directly on the images, allowing full freedom of processing type in the next step and eliminating the need for post-processing alignment operations. This approach will significantly simplify the processing workflow for stereo-PIV Ring-of-Fire configurations in particular.

Although the results do not constitute statistically converged data, they provide initial evidence of aerodynamic differences between single-vehicle operation and following-vehicle scenarios. These findings highlight the potential of the proposed experimental approach and display the feasibility of more comprehensive investigations under controlled and repeatable conditions such as in the Catesby tunnel for the future.

References

- Bosbach, J., Kühn, M., & Wagner, C. (2008). Large scale particle image velocimetry with helium filled soap bubbles. *Experiments Fluids*, 46(3), 3. <https://doi.org/10.1007/s00348-008-0579-0>
- Bounds, C. P., Rajasekar, S., & Uddin, M. (2021). Development of a Numerical Investigation Framework for Ground Vehicle Platooning. *Fluids*, 6(11), 11. <https://doi.org/10.3390/fluids6110404>
- Butcher, D., Knowles, J., Upton, J., Hollis, D., & Erdogdu, O. (2025, June). Full-length Wake Measurement of a Full-Scale Passenger Car using “Ring of Fire” PIV. *16th International Symposium Particle Image Velocimetry – ISPIV 2025*.
- Davila, A., Aramburu, E., & Freixas, A. (2013). *Making the best out of aerodynamics: Platoons*. SAE Technical Paper.
- Ebrahim, H., Dominy, R., & Martin, N. (2020). Aerodynamics of electric cars in platoon. *Proceedings Institution Mechanical Engineers, Part D Journal Automobile Engineering*, 235(5), 5. <https://doi.org/10.1177/0954407020965028>
- Erdogdu, A. O., Hollis, D., Charogiannis, A., Nila, A., Boaler, J., & Berg, T. (2025, June). Historic Vehicle Wake Analysis: “Ring-of-fire” PIV Measurements on the Longest Surviving Jaguar E-Type. *21th International Symposium Flow Visualization*.
- Hüttig, S., Gericke, T., Sciacchitano, A., & Akkermans, R. A. D. (2023). Automotive on-road flow quantification with a large scale Stereo-PIV setup. *15th International Symposium Particle Image Velocimetry – ISPIV 2023*. <https://doi.org/http://hdl.handle.net/20.500.12680/5h73q343c>

- Hüttig, S., Kühn, M., Gericke, T., Sciacchitano, A., & Akkermans, R. A. D. (2025). On-road vehicle aerodynamics with a large-scale stereoscopic-PIV setup: "the Ring of Fire. In *Experiments in Fluids* (10.; Number 10.). Springer Science and Business Media LLC.
<https://doi.org/10.1007/s00348-025-04025-w>
- Nagaoka, H., Yenerdag, B., Ambo, K., Philips, D., Ivey, C., Brès, G., & Bose, S. (2024). Prediction of aerodynamic drag in suvs with different specifications by using large-eddy simulations. *WCXSAEWorldCongressExperience*.
- Novara, M., Schanz, D., & Schroeder, A. (2023). Two-Pulse 3D particle tracking with Shake-The-Box. *Experiments Fluids*, 64(5), 5. <https://doi.org/10.1007/s00348-023-03634-7>
- Schanz, D., Gesemann, S., & Schröder, A. (2016). Shake-The-Box: Lagrangian particle tracking at high particle image densities. *Experiments Fluids*, 57(5), 5. <https://doi.org/10.1007/s00348-016-2157-1>
- Sciacchitano, A., Caridi, G. C. A., & Scarano, F. (2015). A Quantitative Flow Visualization Technique for On-site Sport Aerodynamics Optimization. *ProcediaEngineering*, 112, 412–417.
<https://doi.org/10.1016/j.proeng.2015.07.217>
- Shimoyama, H. (2026). Introduction to Catesby Aero Research Facility, CARF, the Coast-Down Tunnel Proving Ground. *WCXSAEWorldCongressExperience370157*.
- Wiedemann, J., & Potthoff, J. (2003). The New 5-Belt Road Simulation System of the IVK Wind Tunnels - Design and First Results. *SAETechnicalPaperSeries*. <https://doi.org/10.4271/2003-01-0429>